Department I - C Plus Plus

Modern and Lucid C++
for Professional Programmers

Week 3 – Iterators and Algorithms

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Recap Week 2

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`<iosfwd>`, `<istream>`, `<ostream>` and `<iostream>` Headers

- **`<iosfwd>` contains only the declarations for std::ostream and std::istream**
  - In header files (.h) this is usually sufficient when the streams are only used in function declarations
- **`<istream>` and `<ostream>` contain the implementation of the corresponding stream, operators**
  - Usually, these are required in source files (.cpp) when the streams are actually used in functions
- **`<iostream>` contains all of the above and additionally `std::cout`, `std::cin`, `std::cerr`**
  - This is only required in the source file containing the `main()` function, because only there the global standard IO variables shall be used
- **General advice: only use the minimally required header**

Working with std::string

```cpp
#include <iostream>
#include <string>

void askForName(std::ostream & out) {
  out << "What is your name? ";
}

std::string inputName(std::istream & in) {
  std::string name{};
  in >> name;
  return name;
}

void sayGreeting(std::ostream & out, std::string name) {
  out << "Hello " << name << ", how are you?\n";
}

int main() {
  askForName(std::cout);
  sayGreeting(std::cout, inputName(std::cin));
}
```

Preview References

```
void askForName(std::ostream & out)
```

- **`std::string` and built-in types represent values**
  - Can be copied and passed-by-value
  - No need to allocate memory explicitly for storing the chars
- **Some objects aren't values, because they can not be copied:**
  - Streams representing the program's I/O
- **Functions taking a stream object must take it as a reference, because they provide a side-effect to the stream (i.e., output characters)**
- **Reference parameters are marked with `'&'` (ampersand)**
- **In Java all objects are passed as references! (not the same kind of references as in C++!)**
  - Same name, different concept

Caution: Call Sequence

- **Statements are sequenced by ; (semicolon)**
- **Within a single expression, such as a function call, sequence of evaluation is unspecified! (except for the comma operator ,)**
  - C++17 introduced more defined sequencing relations

```
void sayGreeting(std::ostream & out,
                 std::string name1,
                 std::string name2){
  out << "Hello " << name1 << ", do you love " << name2 << "?\n";
}

int main() {
  askForName(std::cout);
  sayGreeting(std::cout,
              inputName(std::cin),
              inputName(std::cin));
}
```

DANGER

Unspecified Behavior

`std::vector<T>` and its Iterators

Goals:

- You can use an `std::vector` in your code
- You know how to get and use iterators of an `std::vector`

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Introduction to `std::vector<T>`

`#include <vector>`

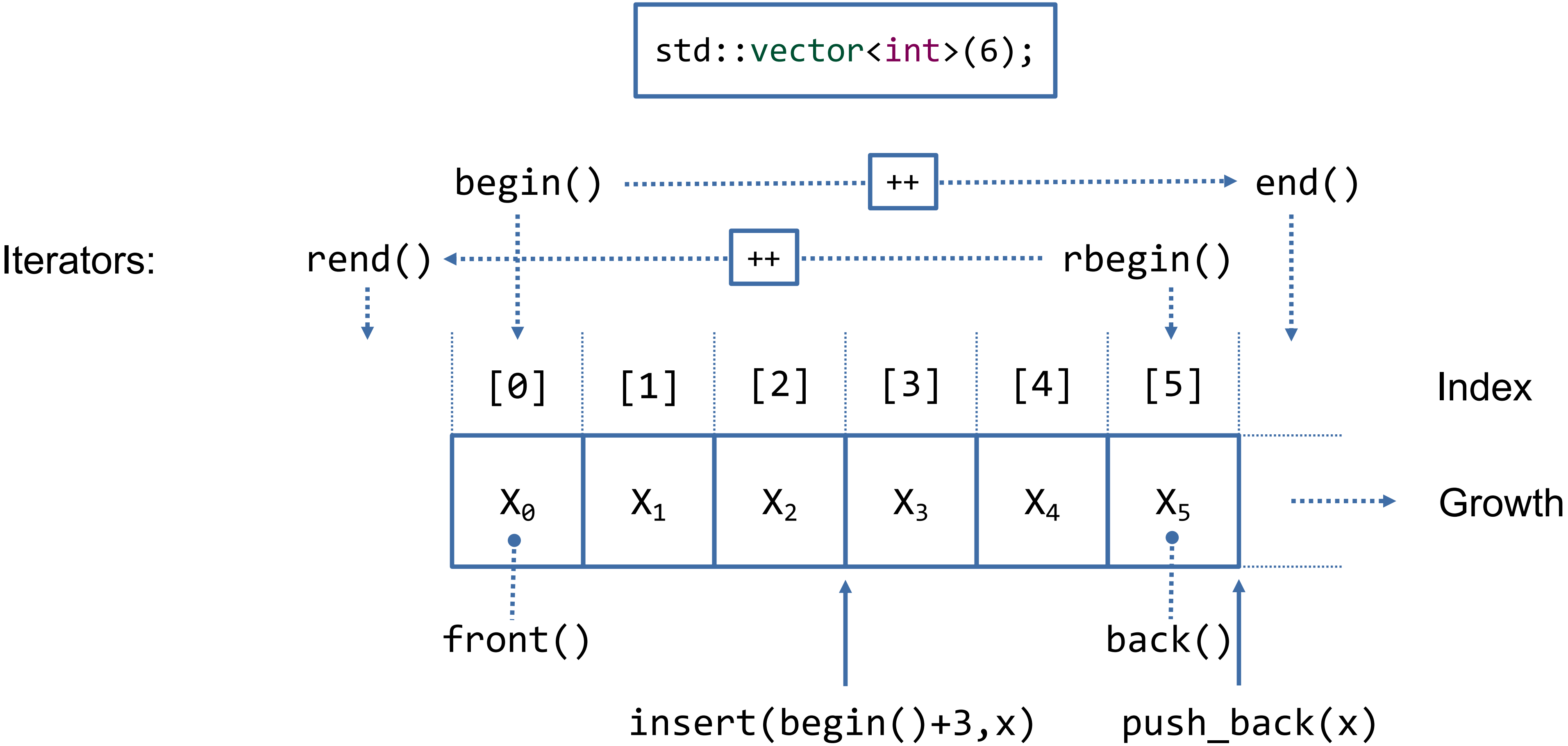
```
std::vector<int>{1, 2, 3, 4, 5};
```

- **C++'s std::vector<T> is a Container = contains its elements of type T (no need to allocate them)**
  - java.util.ArrayList<T> is a collection = keeps references to T objects (must be “new”ed)
  - T is a *template type parameter* (= placeholder for type)
- **std::vector can be initialized with a list of elements**
  - Otherwise it is empty: `std::vector<double> vd{};`
  - Other construction means might need parentheses (legacy)
- **When an initializer is given, the element type can be deduced!**

```
std::vector{1, 2, 3, 4, 5};
```

```
std::vector{};
```

std::vector<T> Overview



- **Parenthesis at definition allow providing initial size, when type of elements is a number**
  - `std::vector<std::string> words{6};` works

Bad Style Iteration

```
for (size_t i = 0; i < v.size(); ++i) {
  std::cout << "v[" << i << "] = " << v[i] << '\n';
}
```

- **You can index a vector like an array**
  - CAUTION: No bounds check!
  - Accessing an element outside the valid range is Undefined Behavior

- **Index variable type is "unsigned"**
  - `size_t` or `std::vector<T>::size_type`
- **Accessing elements with `at()` checks bounds**
  - `std::out_of_range exception` is thrown when accessing an invalid index

```
for (size_t i = 0; i < v.size(); ++i) {
  std::cout << v.at(i) << '\n';
}
```

Bad Style Iteration – Problematic Example

- **Print all elements except the last**

```
void printButLast(std::vector<char> const & values) {
  for (size_t i = 0; i < values.size() - 1; ++i) {
    std::cout << "v[" << i << "] = " << values[i] << '\n';
  }
}

int main() {
  std::vector letters{'a', 'b', 'c', 'd'};
  printButLast(letters);

  std::vector<char> empty{};
  printButLast(empty);
}
```

Undefined Behavior

- **Index-based iteration is used only if the actual index value is required!**

Element Iteration (Ranged-Based for)

- **Advantage: No index error possible, but still need to figure out what loop body does**
- **Works with all containers, even value lists `{1, 2, 3}`**

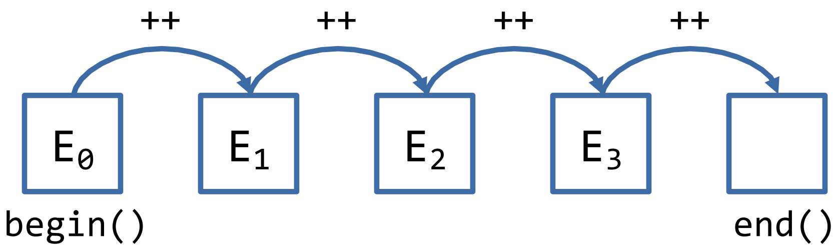
	const: • element cannot be changed	**non-const:** • element can be changed

reference:
• element in vector is accessed
	`for (auto const & cref : v) {`
	`  std::cout << cref << '\n';`
	`}`
		`for (auto & ref : v) {`
		`  ref *= 2;`
		`}`

copy:
• loop has own copy of the element
	`for (auto const ccopy : v) {`
	`  std::cout << ccopy << '\n';`
	`}`
		`for (auto copy : v) {`
		`  copy *= 2;`
		`  std::cout << copy << '\n';`
		`}`

C++ Iterators

`#include <iterator>`



- **Each container provides iterators**
- **There is always a pair of iterators denoting begin and end of an iteration**
  - `std::begin(v)` and `std::end(v)`
  - `v.begin()` and `v.end()`
- **C++ iterators don't know the end of an iteration (no `hasNext()` member)**
- **Operations:**
  - Comparison: You have to compare the current iterator to end
  - Accessing the current element: * operator
  - Step to the next element: ++ operator

```
iterator != std::end(v)
```

```
*iterator
```

```
++iterator
```

for-loop Iteration with Iterators

```
for (auto it = std::begin(v); it != std::end(v); ++it) {
  std::cout << (*it)++ << ", ";
}
```

- **Start with `std::begin(v)`**
- **Compare against `std::end(v)`**
- **Access element with `*iterator`**
  - Changing the element in a non-const container is possible in this way
- **Guarantee to just have read-only access with `std::cbegin()` and `std::cend()`**

```
for (auto it = std::cbegin(v); it != std::cend(v); ++it) {
  std::cout << *it << ", ";
}
```

- **This kind of iteration is only useful if the position (the iterator) is required in the loop**

Using Iterators with Algorithms

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Goals:

- You know some basic algorithms of the standard library
- You can apply the algorithms to **`std::vector`** iterators
- You should want to avoid writing hand-written loops

Algorithms in the Standard Library

`#include <algorithm>`

- **Each algorithm takes iterator arguments**
  - The range(s) of elements to apply an algorithm to is specified by iterators (C++20 introduces "Ranges")
- **The algorithm does what its name tells us**
- **Example: Counting values**
  - Algorithm `std::count` returns the number of occurrences of a value in range
  - Works with all ranges denoted by a pair of iterators

```
size_t count_blanks(std::string s) {
  size_t count{0};
  for (size_t i = 0; i < s.size(); ++i) {
    if (s[i] == ' ') {
      ++count;
    }
  }
  return count;
}
```

```
//The implementation is so simple it
//is not even necessary to create
//a separate function

size_t count_blanks(std::string s) {
  return std::count(s.begin(), s.end(), ' ');
}
```

Algorithm Examples: `std::accumulate` and `std::distance`

- **Summing up all values in a vector (with `std::accumulate`)**
  - Applies + operator to elements
  - Requires the initial value

```
std::vector<int> v{5, 4, 3, 2, 1};
std::cout << std::accumulate(std::begin(v), std::end(v), 0)<< " = sum\n";
```

- **Number of elements in range (with `std::distance`)**
  - Containers provide a `size()` member function
  - Useful if you only have iterators

```
void printDistanceAndLength(std::string s) {
  std::cout << "distance: "<< std::distance(s.begin(), s.end()) <<'\n';
  std::cout << "in a string of length: "<< s.size()<<'\n';
}
```

Algorithm Example: `for_each`

```cpp
void print(int x) {
  std::cout << "print: "<< x << '\n';
}
void printAll(std::vector<int> v) {
  std::for_each(std::crbegin(v), std::crend(v), print);
}
```

- **Like `for` statement: Executes an action for each element in a range**
- **Last argument is a function ("first class value" in C++) that takes one parameter of the element type**
- **Using `std::cout` outside `main` is discouraged**
  - What can we do if we want to print to a given `std::ostream`?

```cpp
void print(int x, std::ostream & out) {
  out << "print: "<< x << '\n';
}
void printAll(std::vector<int> v, std::ostream & out) {
  std::for_each(std::crbegin(v), std::crend(v), print(?, out));
}
```

Lambda Force to the Rescue!

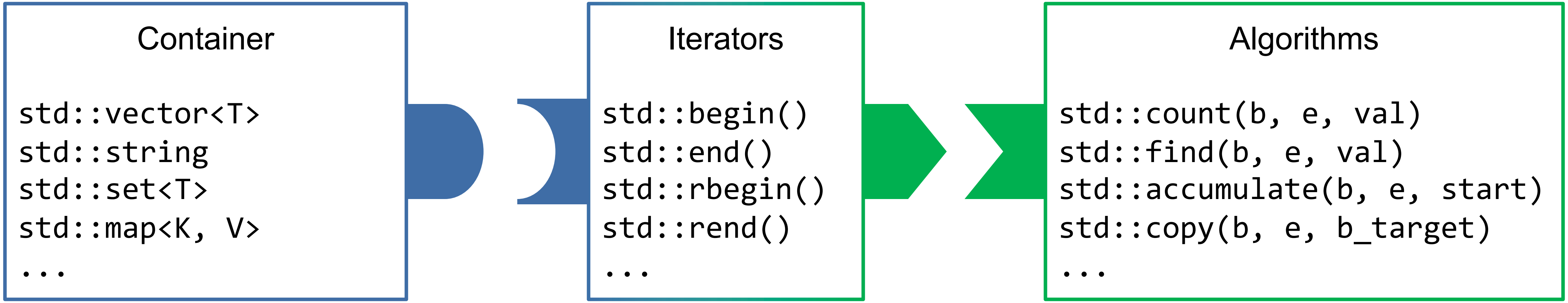
```
void printAll(std::vector<int> v, std::ostream & out) {
  std::for_each(std::crbegin(v), std::crend(v), [&out](auto x) {
    out << "print: "<< x << '\n';
  });
}
```

Lambda structure:

```
[<capture>](<parameters>) -> <return-type> {
  <statements>
}
```

- A lambda expression creates a function object on the fly that can be passed to an algorithm
  - The created function is called from within the algorithm
  - Capture names variables taken from the surrounding scope, or define new ones
    (= copy, & -> reference, rename possible, type deduced)
- Parameters are like function parameters, if any, but you can use auto
- The return_type can be omitted if `void` or consistent return statements in the body (-> compiler knows)

Iterators Connect Containers and Algorithms



Container

```
std::vector<T>
std::string
std::set<T>
std::map<K, V>
...
```

Iterators

```
std::begin()
std::end()
std::rbegin()
std::rend()
...
```

Algorithms

```
std::count(b, e, val)
std::find(b, e, val)
std::accumulate(b, e, start)
std::copy(b, e, b_target)
...
```

- **Containers cannot be used with algorithms directly**
  - Iterators connect containers and algorithms

Appending Elements to an std::vector<T>

`#include <iterator>`

- **Inserting elements into an `std::vector<T>`**
  - Append: `v.push_back(<value>);`
  - Insert anywhere: `v.insert(<iterator-position>, <value>);`
- **When using the `std::copy` algorithm the target has to be an iterator too**

```
std::copy(<input-begin-iterator>, <input-end-iterator>, <output-begin-iterator>);
```

- **Can we do the following?**

```
std::vector<int> source{1, 2, 3}, target{};
std::copy(source.begin(), source.end(), target.end());
```

DANGER

Undefined Behavior

- **We need an `std::back_inserter` or an `std::inserter`**

```
std::vector<int> concat(std::vector<int> first, std::vector<int> second) {
  std::copy(second.begin(), second.end(), std::back_inserter(first));
  return first;
}
```

Filling an std::vector<T> With Values

`#include <iterator>`

- **Filling a vector with std::fill requires a vector with existing elements to be overwritten**

```cpp
std::vector<int> v{};
v.resize(10);
std::fill(std::begin(v), std::end(v), 2);
```

```cpp
std::vector<int> v(10);
std::fill(std::begin(v), std::end(v), 2);
```

Caution: Requires round parentheses in case of a vector with numeric elements, otherwise it would get 1 element whose value is 10

- **Or create a vector directly filled with 10 2s**
  - The element type is deduced to be `int` (from 2)

```cpp
std::vector v(10, 2);
```

Filling an std::vector<T> With Different Values

#include <iterator>

- **The algorithms `std::generate()` and `std::generate_n()` fill a range with computed values**
  - Either use `std::back_inserter` or a non-empty container

```
std::vector<double> powerOfTwos{};
std::generate_n(std::back_inserter(powerOfTwos),
                5, [x=1.0] () mutable
                      { return x *= 2.0; }
);
```

```
std::vector<double> powerOfTwos(5);
double x{1.0};
std::generate(powerOfTwos.begin(),
              powerOfTwos.end(),
              [&x] {return x *= 2.0;}
);
```

- **The `std::iota()` algorithm fills a range with subsequent values (1, 2, 3, ...)**

#include <numeric>

```
std::vector<int> v(100);
std:iota(std::begin(v), std::end(v), 1);
```

Finding and Counting Elements

- **`std::find()` and `std::find_if()` return an iterator to the first element that matches the value or condition**
  - If no match exists the end of the range is returned

```
auto zero_it = std::find(std::begin(v), std::end(v), 0);
if (zero_it == std::end(v)){
  std::cout << "no zero found \n";
}
```

- **Similarly `std::count()` and `std::count_if()` return the number of matching elements in a range**

```
std::cout << std::count(v.begin(), v.end(), 42) << " times 42\n";
std::cout << std::count_if(begin(v), end(v), [](int x) {
  return x % 2 == 0;
}) << " even numbers\n";
```

Avoid Programming Your Own Loops (if possible)

- **Writing readable code is about expressing intentions**
  - For many intentions there is matching iterator-based algorithm in the standard library
- **It is superior to use the corresponding algorithm (function call) instead of coding your own loop**
  - Correctness
  - Readability
  - Performance

```cpp
bool contains_with_loop(std::vector<int> const & values, int const v) {
  auto const end = std::end(values);
  for (auto it = std::begin(values); it != end; ++it) {
    if (*it == v) {
      return true;
    }
  }
  return false;
}
```

```cpp
bool contains_with_algorithm(std::vector<int> const & values, int const v) {
  return std::any_of(cbegin(values),cend(values),[v](int i){ return i == v;})
}
```

Iterators for I/O

Goals:

- You can create iterators for **`std::istream`**s and **`std::ostream`**s
- You can specify ranges on streams with stream iterators

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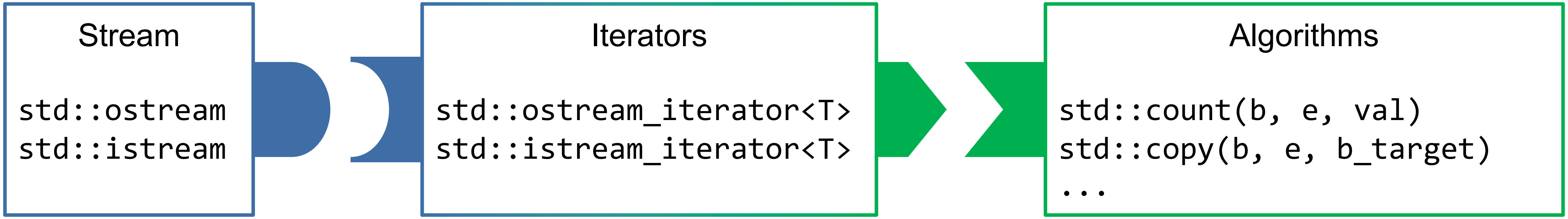
Iterators Connect Streams and Algorithms

`#include <iterator>`



Stream

```
std::ostream
std::istream
```

Iterators

```
std::ostream_iterator<T>
std::istream_iterator<T>
```

Algorithms

```
std::count(b, e, val)
std::copy(b, e, b_target)
...
```

- **Streams (std::istream and std::ostream) cannot be used with algorithms directly**

```
std::copy(std::begin(v), std::end(v), std::ostream_iterator<int>{std::cout, ", "});
```

- **`std::ostream_iterator<T>` outputs values of type `T` to the given `std::ostream`**
  - No `end()` marker needed for ouput, it ends when the input range ends
- **`std::istream_iterator<T>` reads values of type `T` from the given `std::istream`**
  - End iterator is the default constructed `std::istream_iterator<T>{}`
  - It ends when the stream is no longer `good()`

Shorter/Better Type Names With Using Alias Declarations

- The (stream) iterators have a very unpleasant name length, even with auto-completion
- A type alias can help to abbreviate that

```
using <alias-name> = <type>;
```

- Useful if long type names occur more than once
- Example
  - Copy strings from standard input to standard ouput

```
using input = std::istream_iterator<std::string>;
input eof{};
input in{std::cin};
std::ostream_iterator<std::string> out{std::cout, " "};
std::copy(in, eof, out);
```

"Unformatted" Input: std::istreambuf_iterator

- **`std::istream_iterator` uses `operator>>` for input**
  - Disadvantage: It skips white space
- **For an exact copy, we also need the rest**
- **`std::istreambuf_iterator<char>` uses `std::istream::get()` to get every character**
  - This only works with `char`-like types

```
using input = std::istreambuf_iterator<char>;
input eof{};
input in{std::cin};
std::ostream_iterator<char> out{std::cout, " "};
std::copy(in, eof, out);
```

Filling an std::vector<T> from Standard Input

- **To fill a vector from a stream you can either use copy with std::back_inserter(v)**
  - It uses v.push_back() internally

```
using input = std::istream_iterator<int>;
input eof{};
std::vector<int> v{};
std::copy(input{std::cin}, eof, std::back_inserter(v));
```

- **Or, construct the std::vector<T> directly from two iterators**

```
using input = std::istream_iterator<int>;
input eof{};
std::vector<int> const v{input{std::cin}, eof};
```

Summary

- **Output can be done using `ostream`, i.e., `std::cout` and `<<`**
- **Input uses `istream`, i.e., `std::cin` and `>>` to an lvalue**
- **Streams have a state for `eof` and format errors on input**
- **Use algorithms over hand-written loops whenever possible**
- **Iterators specify ranges in C++ and connect streams/containers with algorithms**